Strand Testing at Fermilab

Emanuela Barzi

- **Limits of pressure contact setup**
- **Contributions to contact resistance (measured and calculated)**
- **New sample holders design and performance**

Upgrade of Power Supply

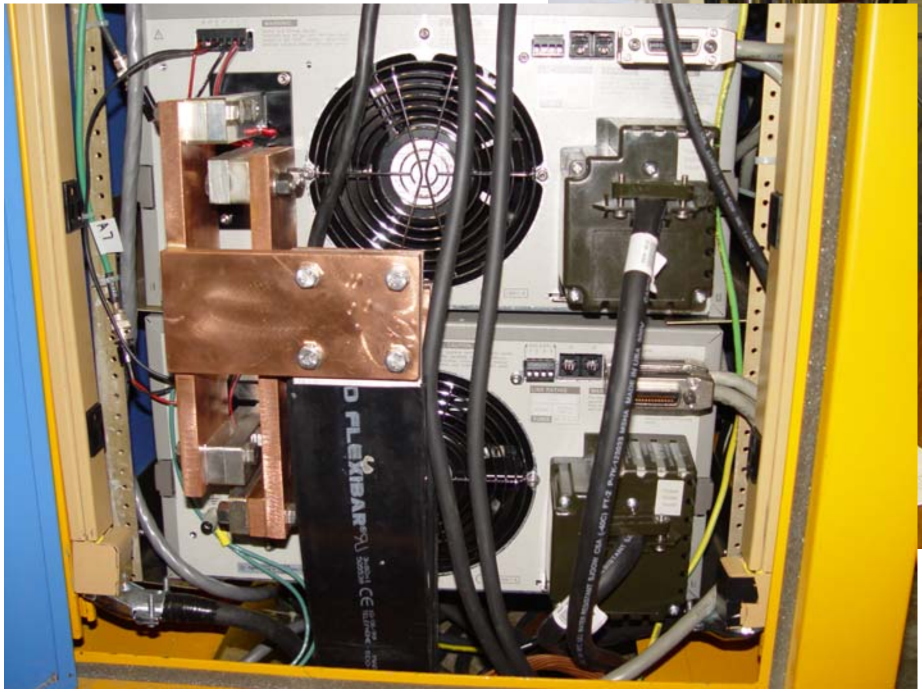
LBNL-FNAL Collaboration Meeting

2 x 6680A AGILENT

895 A / 5 V DC PS

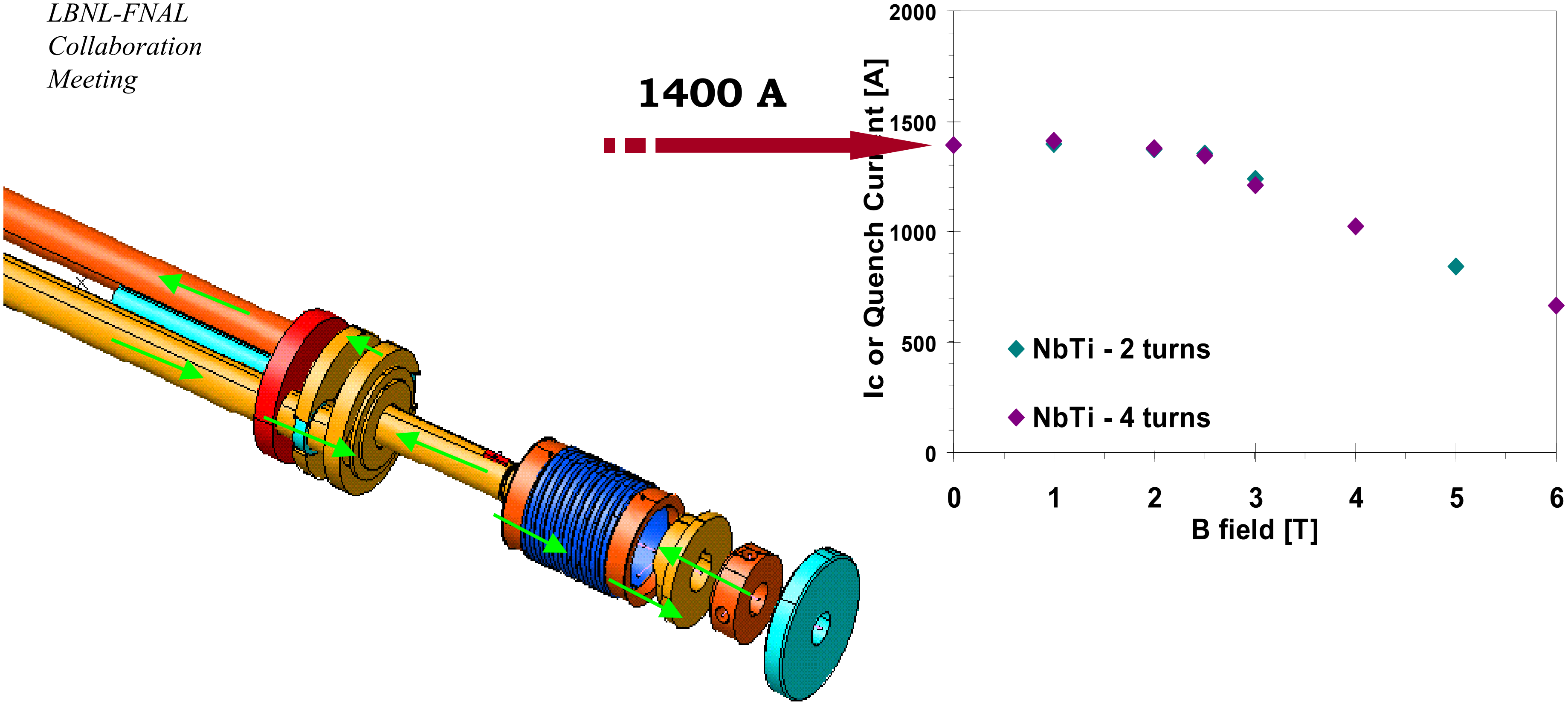
IN PARALLEL

PS LIMIT = 1815 A



Limitations of Existing Probe

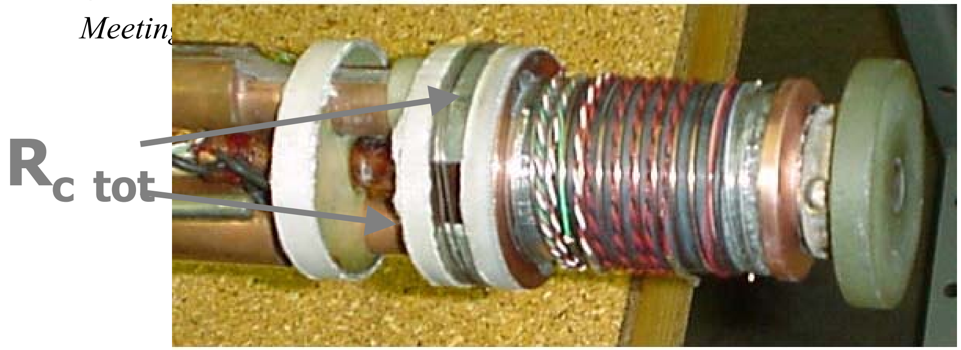
LBNL-FNAL Collaboration Meeting

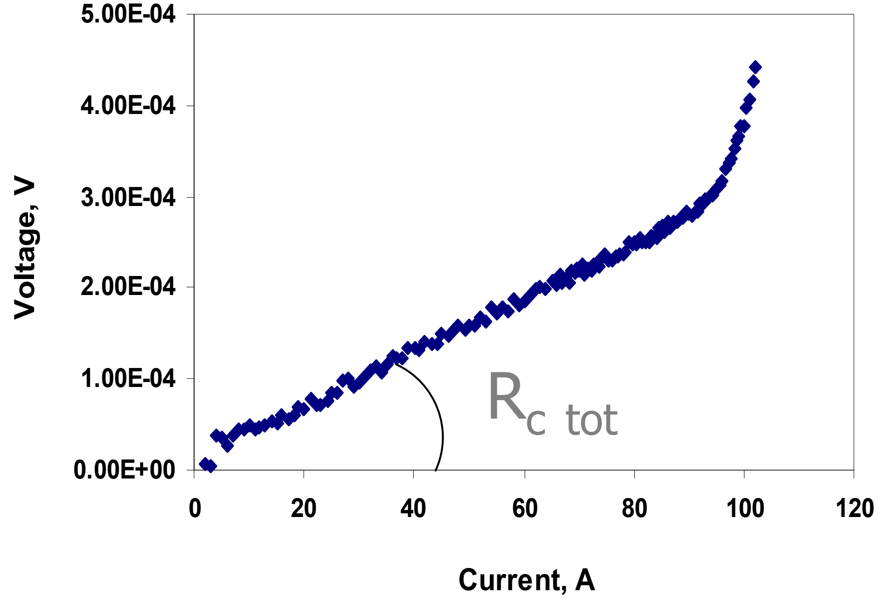


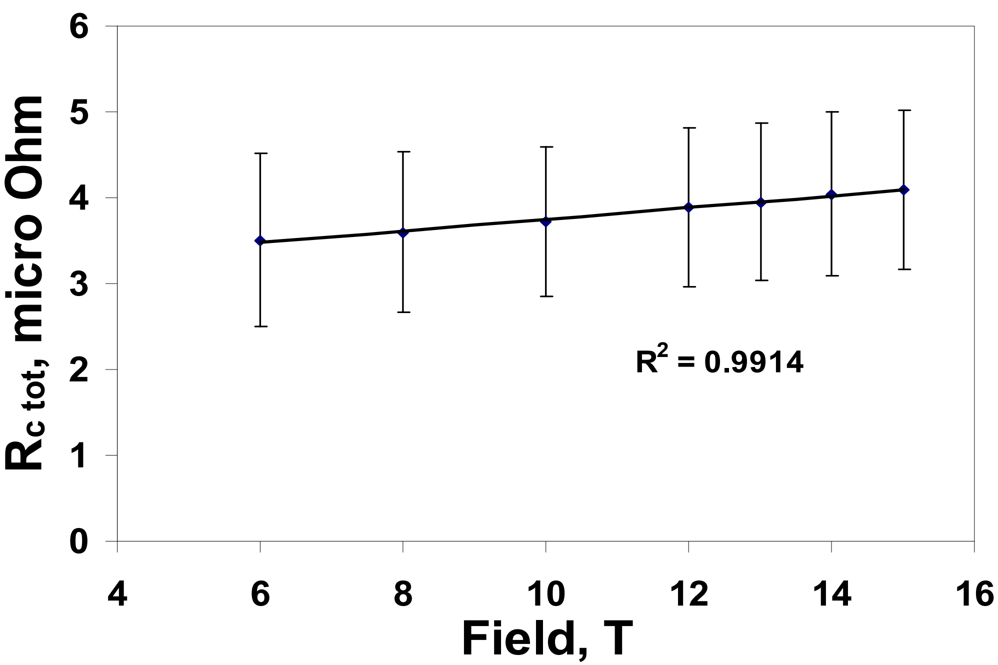
- ❖ **Total contact resistance ~ 4 μOhm**
- ❖ **An estimate of the maximum allowed contact resistance to carry 2000 A ~ 1 μOhm**

Total Contact Resistance – Measurement

LBNL-FNAL Collaboration Meeting







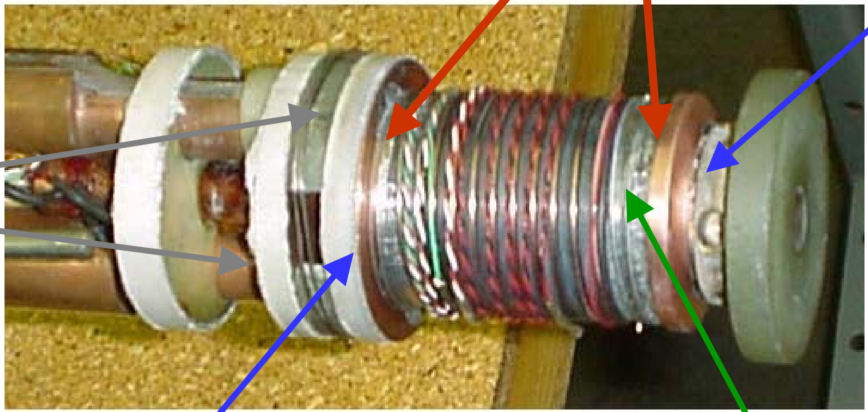
$R_{c\ tot}$ averaged over 34 samples as a function of field

(Spread given by the root mean square of the distributions)

Total Contact Resistance

Contributions

$$R_{C\ tot} = \sum R_{Cu,\ Brass,\ In} + \sum R_{soldered\ turns} + \sum R_{Press.\ contact}$$



Contact Resistance – Calculation

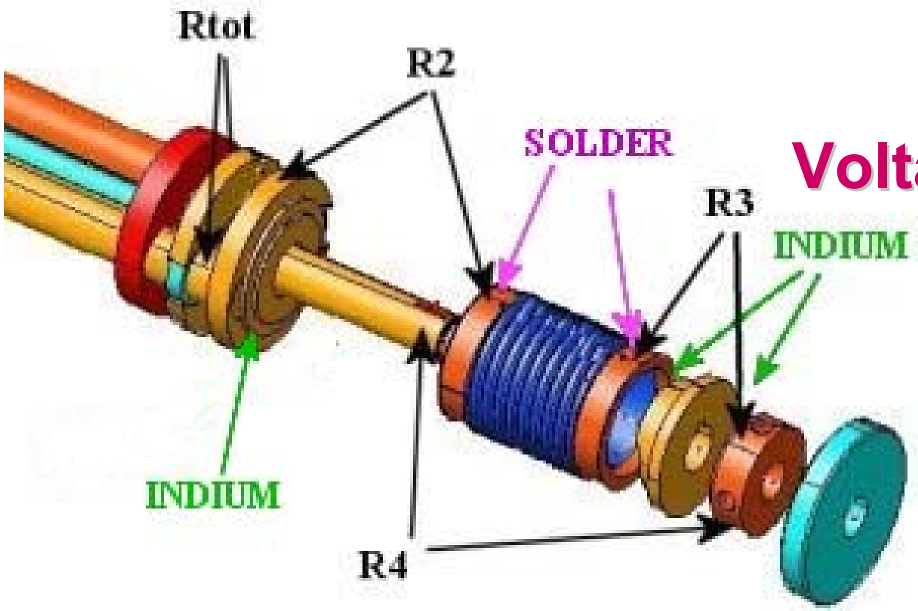
Soldered contact

$$r = \frac{\rho_{Solder,4.2K} \cdot t_{Solder}}{\pi \cdot \phi_{Solder}} = 0.0316 \cdot 10^{-9}\,\Omega \cdot m$$

$$R = \frac{\rho_{Cu,4.2K}}{\pi \cdot \phi_{Cu} \cdot t_{Cu}} 0.01448 \cdot 10^{-4}\,\Omega / m$$

Number of turns	L (mm)	$R_{Junction}$ (nΩ)
2	2	17
4	4	9.8
8	8	7.2

Contact Resistance – Measurements



Single contributions

Voltage tap location

Copper RRR of probe
was measured = 113

R [OHM]	MEASURED at 4.2 K	OTHER CONTRIBUTIONS (Calculated at 4.2 K)			CONTACT RESISTANCE (CORRECTED FROM R)
		COPPER ρ_{Cu}=1.48E-10 Φm	INDIUM ρ_{In}=3.11E- 10 Φm	BRASS ρ_{Br}=6 E-8 Φm	
R2	1.38E-07	1.45E-09	1.35E-10	No brass	**1.36E-07**
R3	3.22E-07	7.27E-10	2.80E-10	1.38E-07	**1.83E-07**
R4	2.81E-06	1.98E-06	No In	1.77E-07	**1.03E-06**

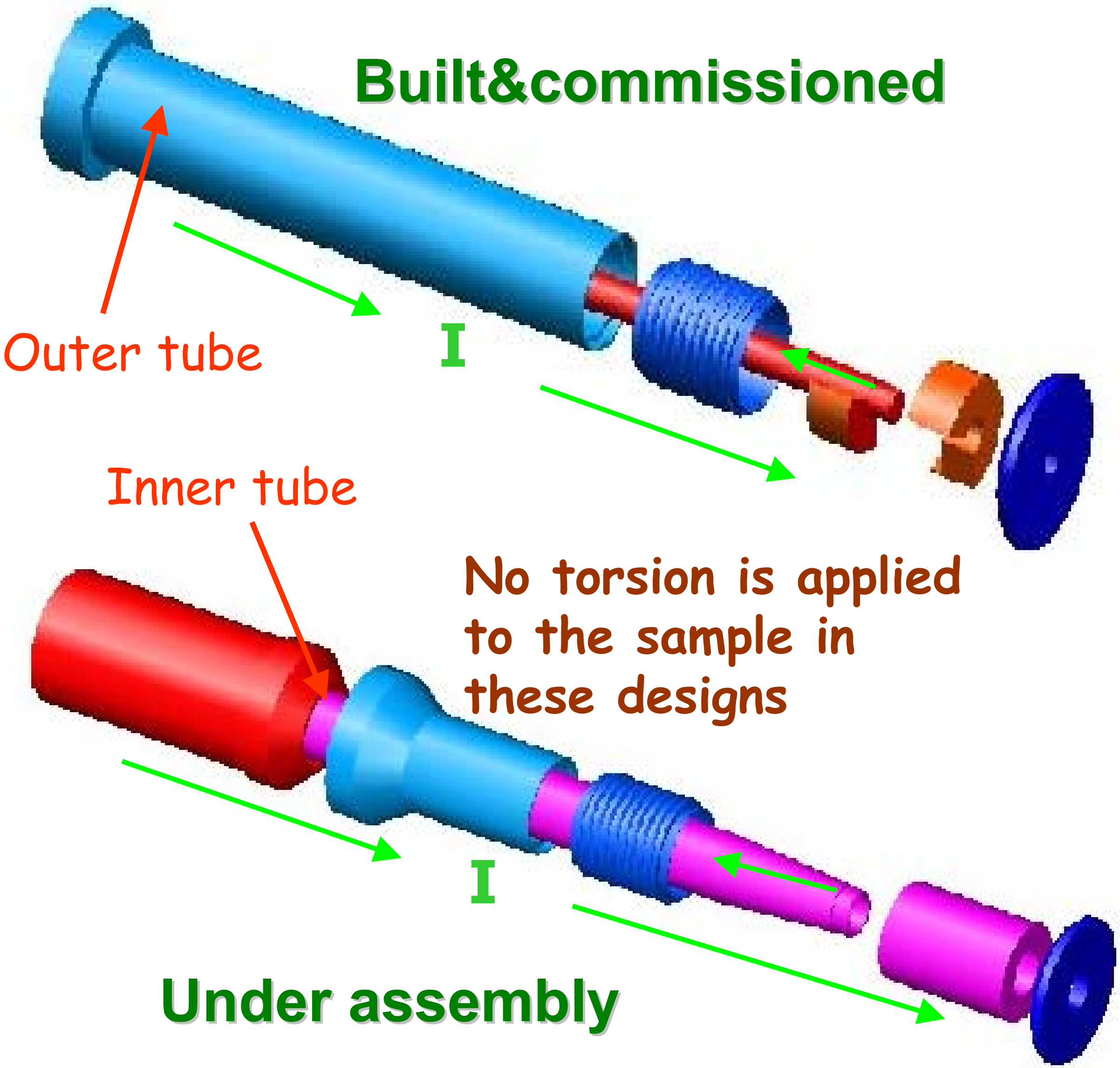
LBNL-FNAL Collaboration Meeting

Comparison – Measurements vs. Calculations

CALC. $R_{\text{Soldered turns}}$ 2 turns	MEAS. $R_{\text{Soldered turns}}$ 2 x 2 turns	CALC. $R_{\text{Pressure contact}}$ Bearing area	CALC. $R_{\text{Pressure contact}}$ Apparent area	MEAS. $R_{\text{Pressure contact}}$ With Indium
17 nΩ	34 nΩ	2.877 μΩ	0.161 μΩ	0.136 μΩ

- **Excellent consistency was found between data and calculations**
- **By flowing within the contact surfaces, Indium makes the apparent area to be the actual contact area for current flow**
- **Pressure contact resistances are only about 1 order of magnitude larger than for soldered contacts**

Sample Holder Designs



Soldered contact

- Sample ends soldered to copper lugs
- Expected contact resistance < 40 nΩ

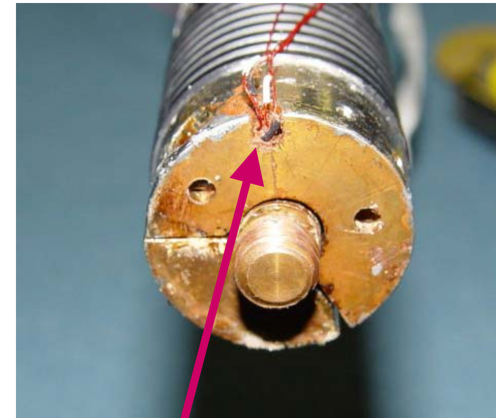
Pressure contact

- Design with contact area ~ previous x4
- Expected contact resistance < 1 $\mu\Omega$

LBNL-FNAL
Collaboration
Meeting

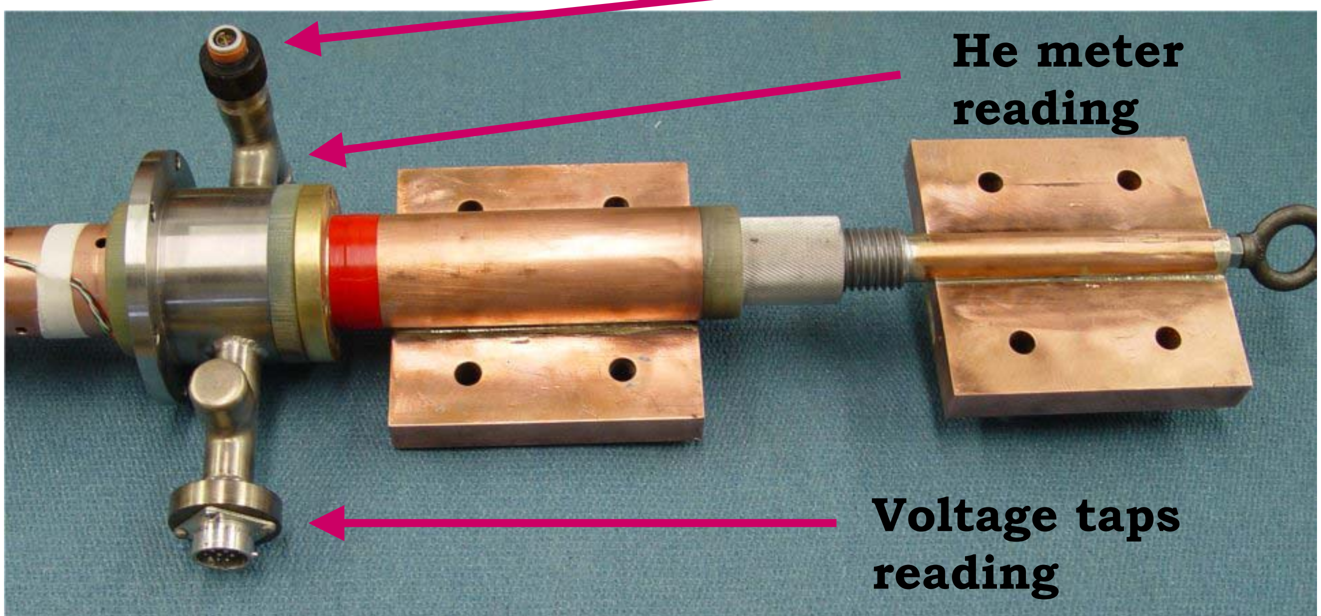
High Current Probe – Soldered contact

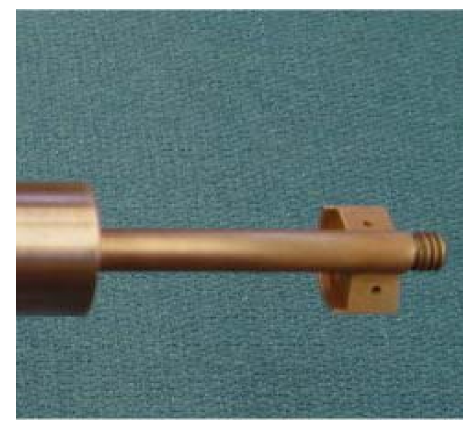
Instrumented sample



Cernox

Cernox reading

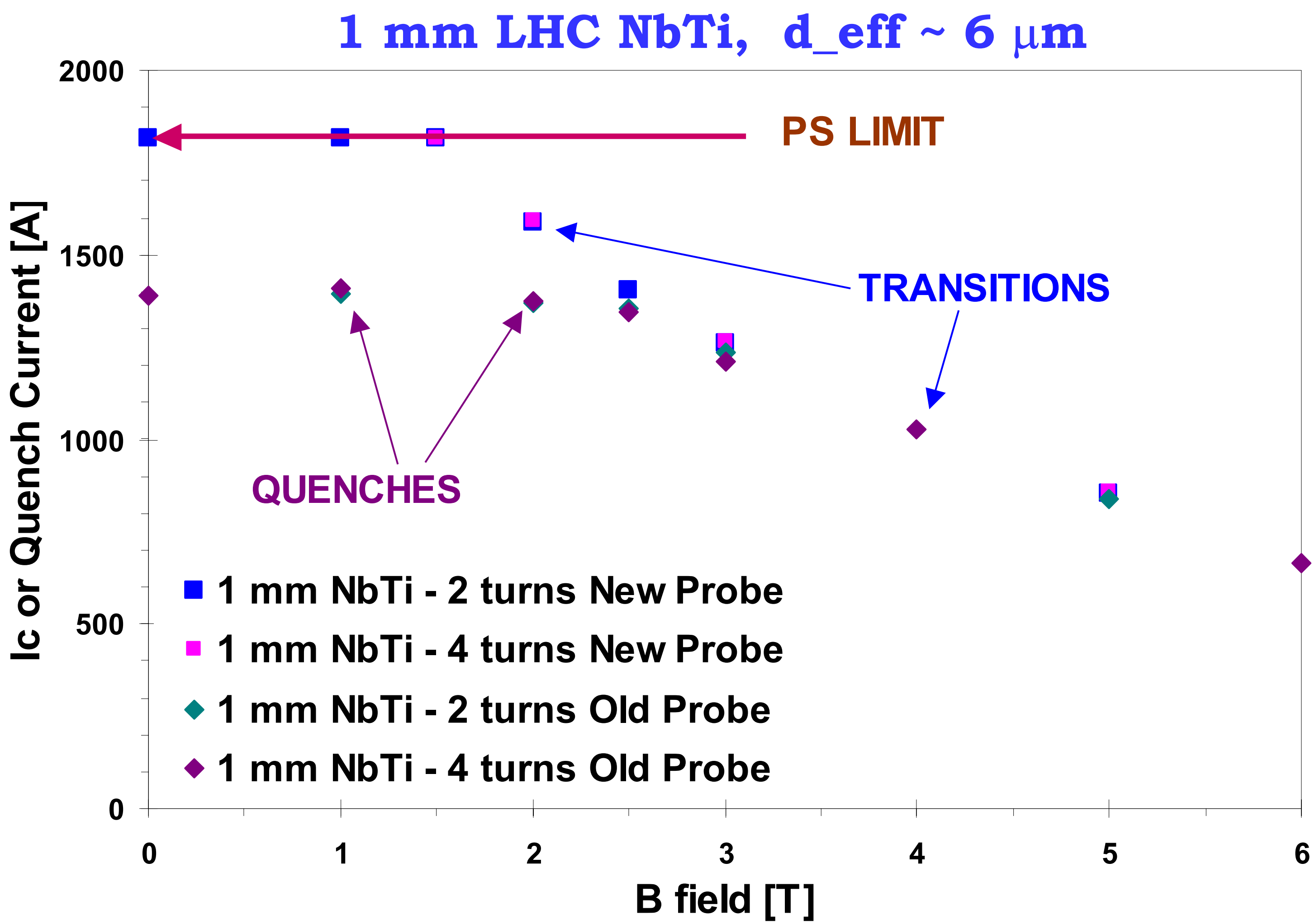




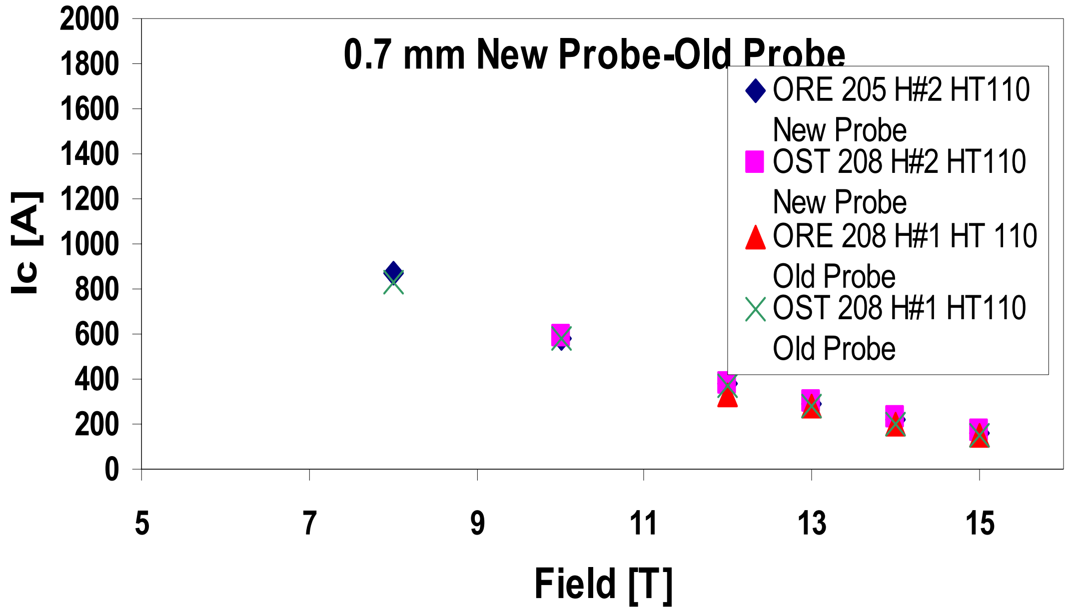
Licia Del Frate's *Laurea* Thesis

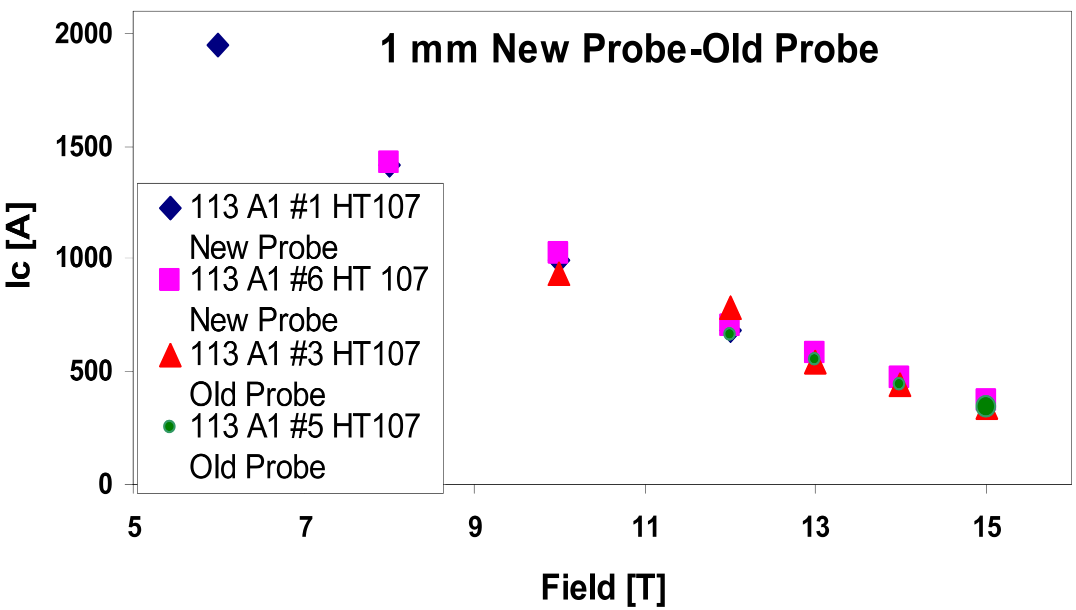
Measurements at Low Fields of Stable Strands

LBNL-FNAL Collaboration Meeting



Comparison – Critical Current Values

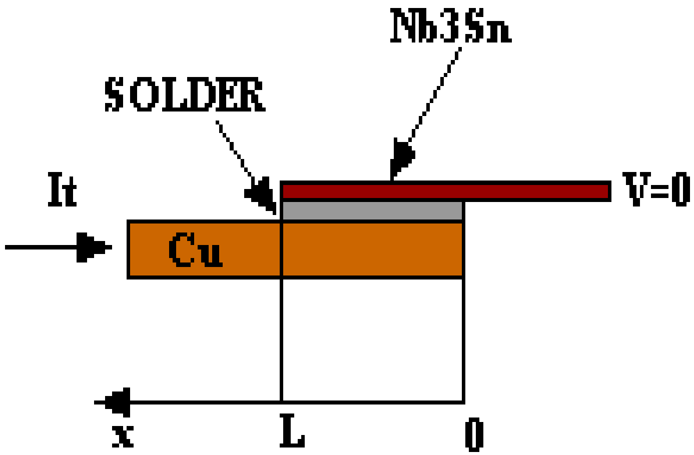




Conclusion – The I_c measurements performed with the new probe are consistent with the regular ones

Contact Resistance – Calculation

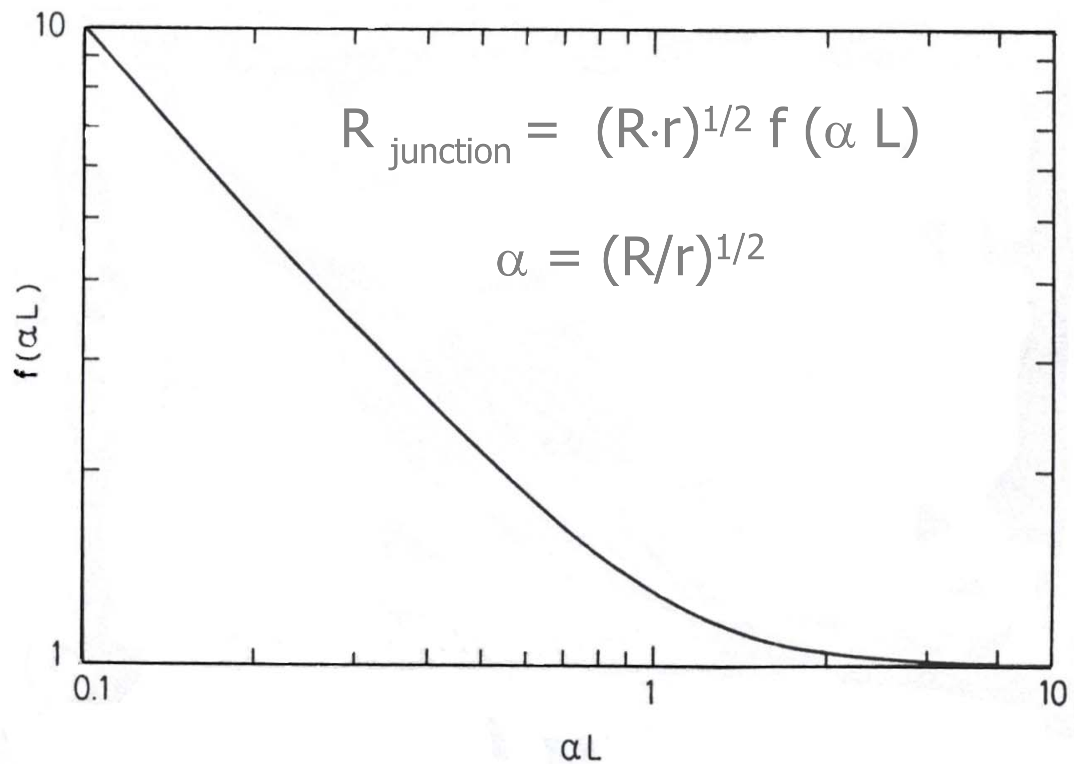
Soldered contact



$$\begin{cases} V(x) = r \cdot \dfrac{dI(x)}{dx} \\ \dfrac{dV(x)}{dx} = I(x) \cdot R \end{cases}$$

$r =$ Solder resistance $\cdot$ length

$R =$ Cu resistance / length



$R_{\text{junction}} = (R \cdot r)^{1/2} f(\alpha L)$

$\alpha = (R/r)^{1/2}$

$$V(L) = I_t \cdot (R \cdot r)^{1/2} \cdot \frac{e^{\alpha L} + e^{-\alpha L}}{e^{\alpha L} - e^{-\alpha L}} = I_t \cdot (R \cdot r)^{1/2} \cdot f(\alpha L)$$

Contact Resistance – Calculation

Pressure contact

Force due to torque *T*

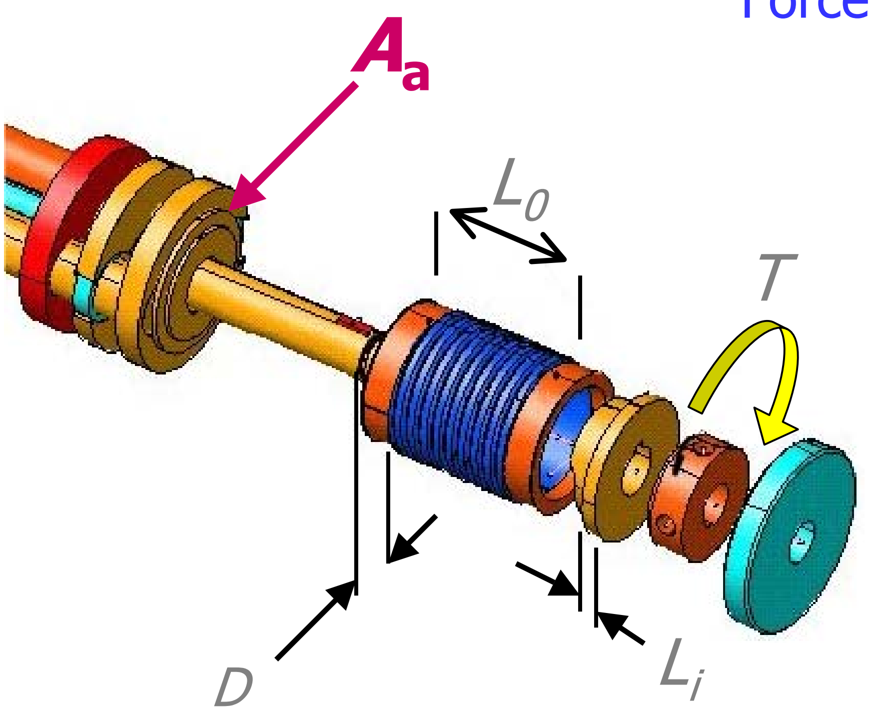
$$F = \frac{T}{0.2D} = 6667 \quad N$$

Force due to differential thermal contraction δ

$$\delta = \varepsilon_{Cu} \cdot L_{Cu} - \varepsilon_{Ti} \cdot L_{Ti}$$

$$\begin{cases} L_{Cu} = L_{Ti} = L_0 = 34.9 \ mm \\ \varepsilon_{Cu}(293 - 4.2 \ K) = 0.32\% \\ \varepsilon_{Ti}(293 - 4.2 \ K) = 0.15\% \end{cases}$$

$$P = \frac{\delta}{\sum \frac{L_i}{A_i \cdot E_i}} = 364 \quad N$$



Thread nominal diameter

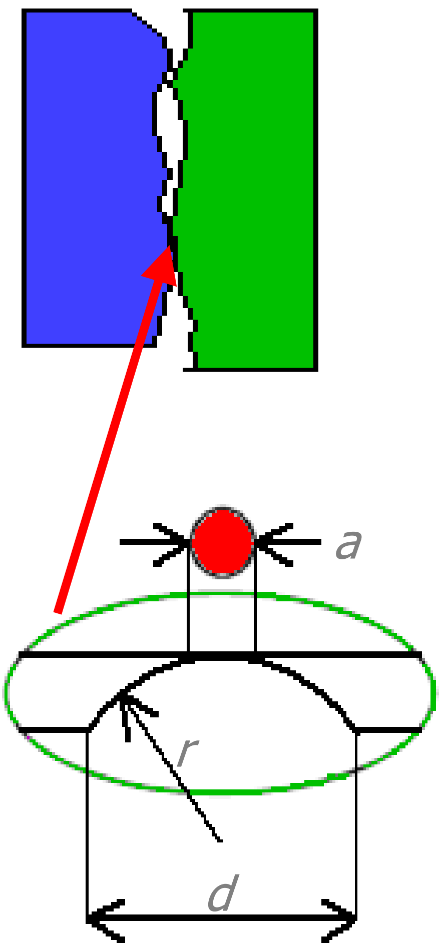
Total pressure on apparent area A_a

$$\bar{p}_a = \frac{F+P}{A_a} = 2.707 \cdot 10^7 \frac{N}{m^2}$$

Contact Resistance – Calculation

LBNL-FNAL Collaboration Meeting

Pressure contact



Actual contact area depends on pressure

From Hertz classic formulae on elastic deformation and contact surfaces, in the case of a sphere against a plane body of same material (with Poisson ratio = 0.3):

$$a = 1.11 \cdot \sqrt[3]{\frac{P_i}{E} \cdot r} = 5.807 \cdot 10^{-7}\ m$$

$$P_i = average \quad load / hump = \bar{p}_a d^2$$

$$r = curvature \ \ radius \ \ of \ \ rugosity \ \ elevation = 4 \cdot 10^{-5}\ m$$

Average pressure on a sphere

$$\bar{p} = \frac{\int_0^a \frac{1.5 \cdot P_i}{\pi \cdot a^3} \cdot \sqrt{a^2 - x^2} \cdot dx}{a} = 4.816 \cdot 10^8 \cdot \frac{N}{m^2}$$

Bearing area A_b

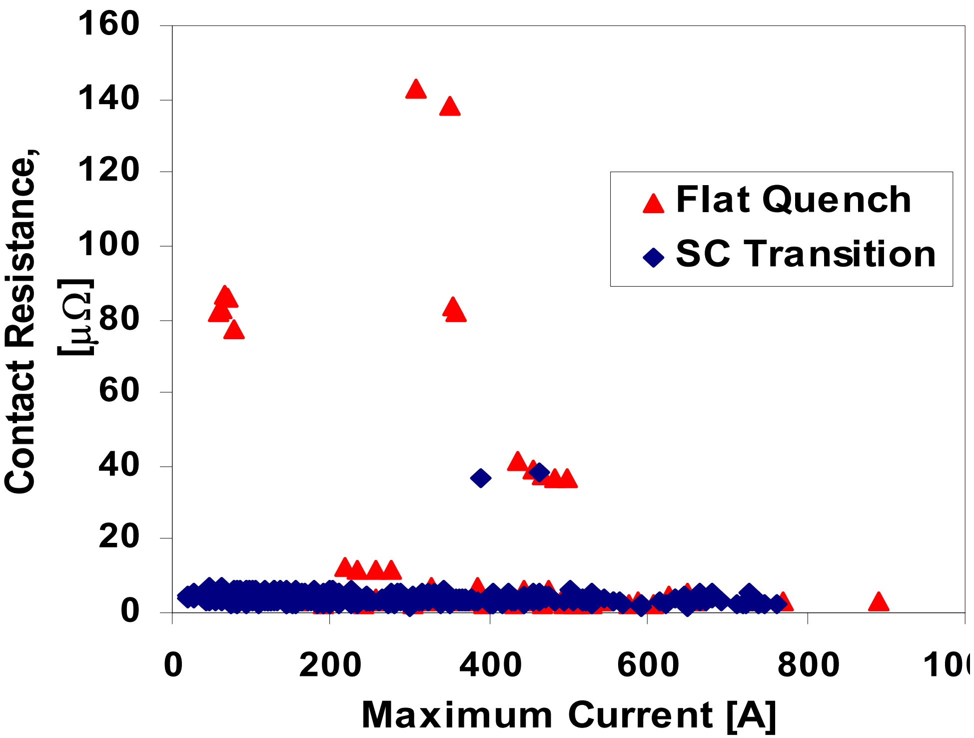
$$\boxed{A_b = \frac{1}{17.795} \cdot A_a}$$

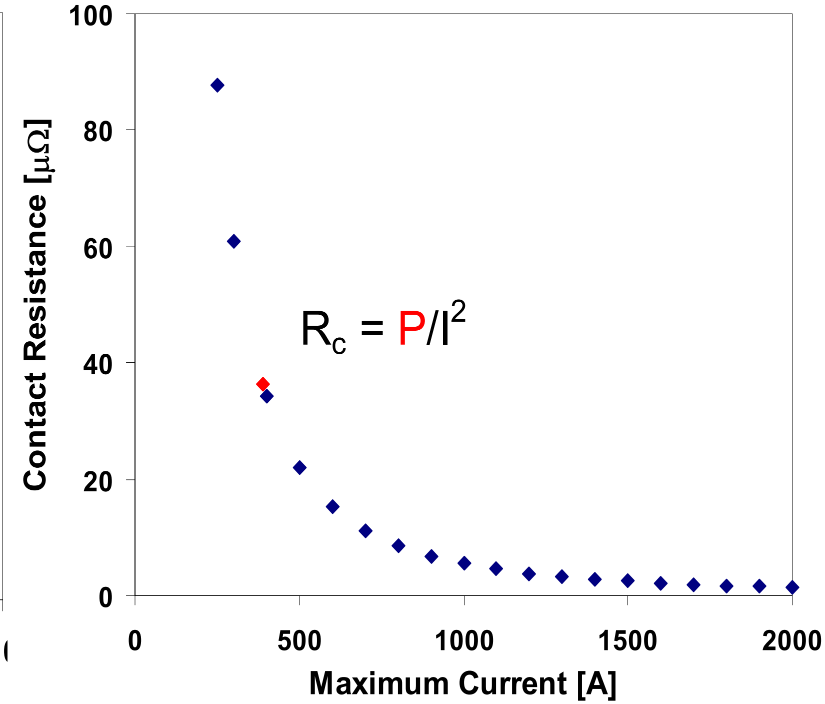
From constriction resistance of a circular conducting surface against a plane body (Kottler, Smythe):

$$R = \frac{\rho}{4 A_b}$$

Effect of Contact Resistance - Extrapolation to 2000 A

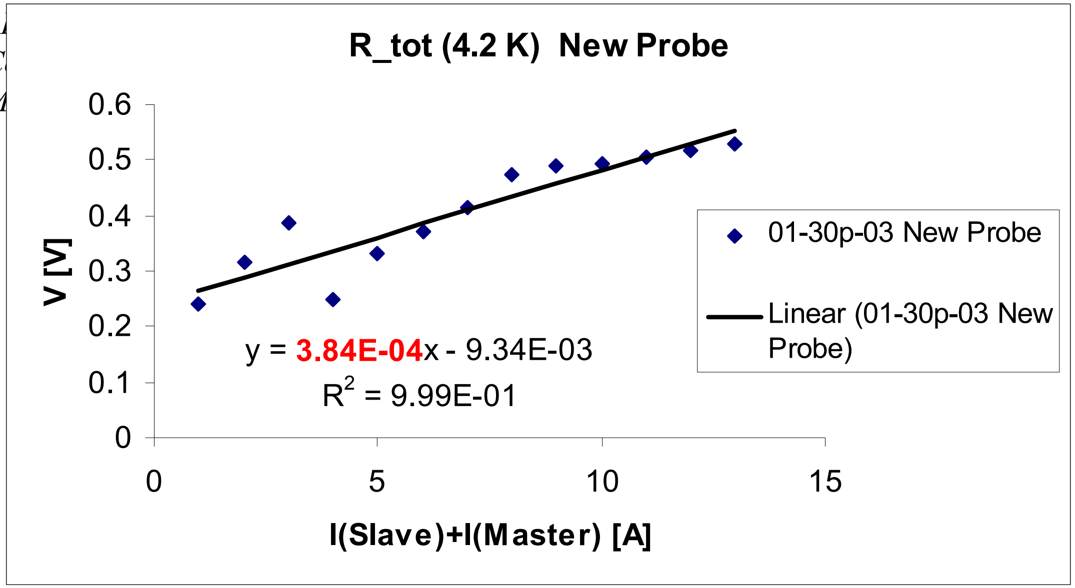
LBNL-FNAL Collaboration

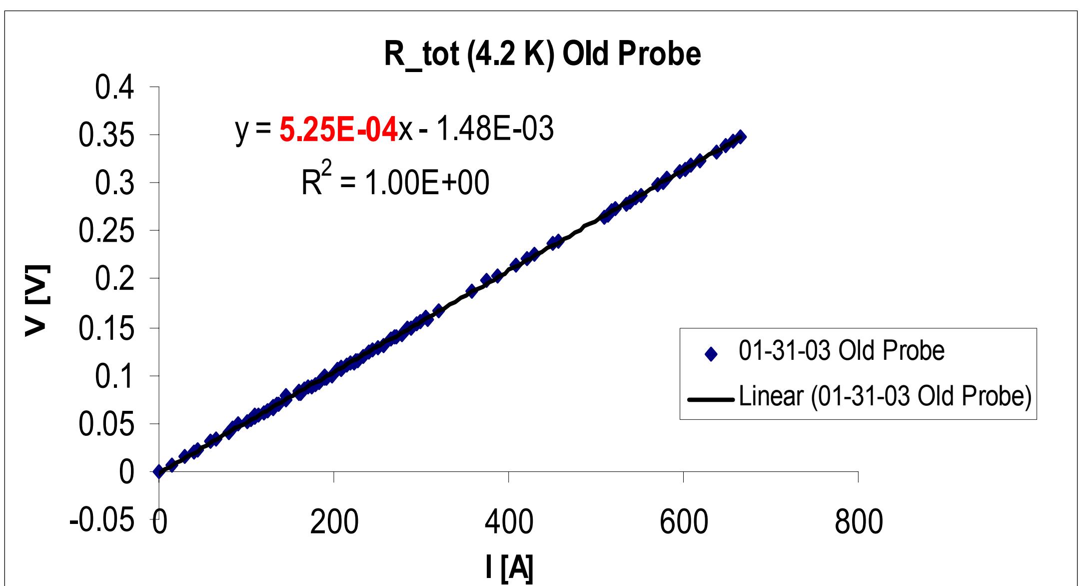




Conclusion – The maximum contact resistance at 2000 A is about 1 μΩ, which is ¼ of present FNAL holder (~ 4 μ Ω)

Comparison - Total Resistance of the Probes





Conclusion – The total resistance of the new probe (without SC splices yet) is already

~ 70% that of the old probe